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ABSTRACT

In the present study, analytical model was developed using the lumped parameter formulation to find out temperature distribution of metal, oil, and refrigerant of a hermetic reciprocating compressor. Correlations of heat transfer coefficients in the literatures were applied to the present model. Motor and mechanical loss, and heat generation during compression process were included in the present model. Parametric study was performed as the following parameters ; heat transfer area, air velocity over the compressor, mixing parameter of the suction muffler, heat conductivity, heat transfer coefficient of metal in the suction and the discharge systems. Experiment was conducted to measure thermal characteristics of the compressor at steady state. Pressure, temperature, and power of the system were measured with refrigerating load. The predicted result of the analytical model has a good agreement with experimental result.

NOMENCLATURE

$A_{i,j}$	: Heat transfer area	$\dot{Q}_i$	: Heat transfer rate
B_i	: Known term	$\dot{S}_i$	: Heat generation
$C_{i,j}$	: Coefficient	T_i	: Temperature
$H_{i,j}$	: Heat conductance	T_∞	: Ambient Temperature
h_i	: Heat transfer coefficient	Δx	: Conduction length
k_i	: Thermal conductivity	ε	: Radiational emissivity
$\dot{m}$	: Mass flow rate of refrigerant	σ	: Stefan-Boltzman constant

INTRODUCTION

It is well known that heat transfer to the suction gas of refrigerant in a reciprocating compressor has adverse effect on volumetric efficiency of a compressor. To improve energy efficiency ratio(EER) of a compressor, heat transfer analysis in a compressor is required. The prediction of heat transfer and temperature distribution in a compressor has been studied because of large effect on a performance of compressor. Although there are publications[(1)~(3)] on heat transfer in a low-side reciprocating compressor, a few work has been reported on analytical model that predict temperature of all elements in the compressor. Furthermore they use measured results and don't consider mixing parameter, that is, the flow portion of direct suction in the suction muffler in the case of indirect suction that is widely applied to a low-side reciprocating compressor.

In this study, lumped parameter formulation was employed to find out the temperature distribution and heat transfer of a reciprocating compressor. Motor and mechanical loss, and heat generation during compression process were included in this model. To evaluate the possibility of improvement in volumetric efficiency, parametric study was performed as the following parameters ; heat transfer area, air velocity over the compressor, mixing parameter of the suction muffler, heat conductivity, heat transfer coefficient of metal in the suction and the discharge systems.

ANALYTICAL MODEL

Lumped Parameter Formulation[3]

In the formulation, the compressor are divided into discrete elements that can be considered to have uniform thermodynamic properties. Applying conservation of mass and the first law of thermodynamics, the equations were formulated to model heat transfer mechanism for several elements.

In case of steady-state, the total rate of heat transfer to an element i can be written as the sum of heat transfer from the other elements either to or from the elements, and the rate of heat generation ($\dot{S}_i$) within the element:

$$\dot{Q}_i = \sum_{j=1}^{n} H_{i,j}(T_j - T_i) + \dot{S}_i = 0 \qquad (1)$$

where $H_{i,j} = \frac{k_i A_{i,j}}{\Delta x}$ (for conduction heat transfer)

$H_{i,j} = h_i A_{i,j}$ (for convective heat transfer)

$H_{i,j} = A_{i,j}\varepsilon\sigma(T_i + T_\infty)(T_i^2 + T_\infty^2)$ (for radiative heat transfer)

The above equation can be written in the following form

$$\sum_{j=1}^{n} C_{i,j} T_j = B_i \qquad (2)$$

where B_i : the rate of heat generation or known parts of the simultaneous equations

Solving this simultaneous equations that are as many as the number of elements, the temperature of elements can be obtained.

In the present study, the compressor is divided to 32 elements. It consists of 13 elements of refrigerant gas with flow path, 16 elements of solid part conformed geometric boundaries, and 3 elements of lubrication oil with flow path. The list of the elements are represented in Table 1. Fig. 1 represents the location of refrigerant gas elements with flow path. Fig. 2 shows location of solid part elements

Mixing Parameter of Indirect Suction[1]

The indirect suction has been widely adopted in a low-side reciprocating compressor to hold noise propagation, separate the lubrication oil from the refrigerant gas and oil mixture, avoid problems of liquid back associated with start-up, and cool the motor.

To characterize the flow portion of direct suction in the suction muffler, mixing parameter(Φ) is defined as the following

$$\Phi = \frac{\dot{m}_{dir}}{\dot{m}} \qquad (3)$$

where $\dot{m}_{dir}$: mass flow rate of direct inflow gas to the suction muffler

$\dot{m}$: total mass flow rate of inflow gas

The mixing parameter is a important parameter in compressor design, because it has a large effect on temperature of suction muffler.

Simulation Procedure

(1) Read input data of geometry of the compressor and the operating condition.

(2) Assume motor rpm, and calculate compression torque and frictional torque. Calculate final motor rpm with the curve-fitting equation of torque-rpm by iteration. Calculate motor loss, mechanical loss, and compression work using calculated rpm.

(3) To calculate convective heat transfer coefficient, assume mass flow rate of refrigerant gas. And to calculate radiational heat transfer coefficient, assume temperature of the shell.

(4) Using correlations from the literatures[4] and geometric dimension, calculate heat transfer conductance and coefficients of the simultaneous equations between lumped mass elements. In this instance, internal radiation terms are ignored on convenience.

(5) Solving simultaneous equations by the Gauss-Jordan method, obtain temperature of elements.

(6) Compare assumed value with calculated value of the shell temperature. When the difference is not in tolerance, calculated temperature is new temperature of the shell and go to the step (4).

(7) If temperature of elements is completely converged, calculate heat transfer conductance and coefficients of the simultaneous equations that include internal radiation terms, and solve new simultaneous equations by Gauss-Jordan method to obtain temperature of elements.

(8) From the temperature and pressure of refrigerant gas in suction chamber and motor rpm, obtain specific volume and mass flow rate of gas. Compare assumed value with calculated value of mass flow rate. When the difference is not in tolerance, calculated value is new mass flow rate and go to the step (4).

(9) Finally, simulation is terminated and results are printed out.

EXPERIMENTAL VALIDATION

In order to verify the analytical model, calorimeter test is necessary. But ASHRAE compressor test condition is severe case comparing with normal operating condition of the household refrigerators. In this study, the household refrigerator was modified to realize steady state operating condition by means of adding artificial cooling load in freezing room. Pressure, temperature and power of the system were measured with refrigerating load.

Fig. 3 shows the comparison of temperature with element number between measured and simulated value on the condition of 30℃ ambient air temperature, -18℃ freezing temperature, and 3℃ refrigerating temperature. A good agreement is obtained in the magnitude and the tendency except stator and discharge part. The discrepancy of stator temperature can be explained by the fact that measured value is surface temperature and simulated is averaged one. In the case of discharge part, the discrepancy may result from problem of temperature probe installation.

PARAMETER STUDY

Ambient Air Velocity

Fig. 3 shows temperature distribution with ambient air velocity over compressor shell. Fig. 7 shows temperature increment of suction gas from suction pipe to suction chamber and volumetric efficiency with ambient air velocity(0m/s, 4.2m/s and 10m/s). As air velocity increases, the superheat degree of suction gas decreases and the volumetric efficiency increases. Temperature of gas in compression chamber at 10m/s lower than that at 0m/s by 11.4℃ and mass flow rate is higher than that by 4.4%.

Mixing Parameter

Fig. 4 and Fig. 8 shows results with mixing parameter. Value of $\Phi=0$ represents complete mixing in this case no direct suction occurs in suction muffler of the compressor. On the other hand, value of $\Phi=1$ means that all suction gas is directly sucked to suction muffler. The results show that temperature of gas in suction chamber reduces and volumetric efficiency increases with increase of mixing parameter.

Thermal Conductivity of Discharge Plenum

The results with conductivity of discharge plenum material(20, 53, 151 and 300 $W/m \cdot K$) are shown Fig. 5

and Fig. 9. Conductivity of discharge plenum material and frame is 151($W/m \cdot K$) and 53($W/m \cdot K$) respectively from the literature[5]. Temperature of gas in compression chamber at 20($W/m \cdot K$) is lower than that at 300 ($W/m \cdot K$) by 7.9℃ and mass flow rate is higher than that by 3.1%.

Overall Heat Transfer Coefficient of Suction System

It is useful to evaluate possibility of improvement of efficiency by means of insulation of suction systems : suction muffler, pipe between suction muffler and suction plenum, suction plenum.

Overall heat transfer coefficient of suction system in case of insulation can be expressed as the following

$$U = \frac{1}{\frac{z}{k} + \frac{1}{h}} \tag{4}$$

Fig. 6 and Fig. 10 represent results in case of insulation of suction system, namely, overall heat transfer coefficient is fall to half. The results show that the temperature difference of suction chamber gas is 7.8℃ and increment of volumetric efficiency is 3.1%. Therefore it is known that insulation of suction system is very effective to improvement of performance of the compressor.

CONCLUSIONS

(1) Comparing predicted results with measured results, a good agreement is obtained in the magnitude and the tendency.

(2) As air velocity increases, the superheat degree of suction gas decreases and the volumetric efficiency increases.

(3) Temperature of gas in suction chamber reduces and volumetric efficiency increases with increase of mixing parameter.

(4) Temperature of gas in suction chamber reduces and volumetric efficiency increases with decrease of the thermal conductivity of the discharge plenum.

(5) When the overall heat transfer coefficient was decreased to half value by the insulation of suction system, volumetric efficiency increases by about 3.1%.

(6) This analytic model is very useful to understand effect of parameters on heat transfer between elements in the compressor.

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Tables and Figures

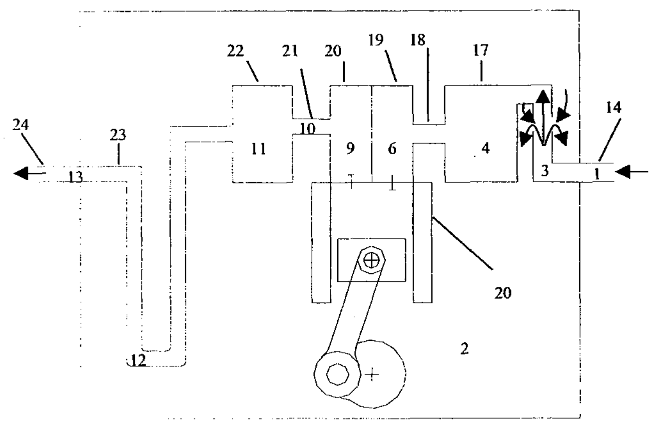

Fig. 1 Block diagram of lumped mass elements of refrigerant gas with refrigerant flow

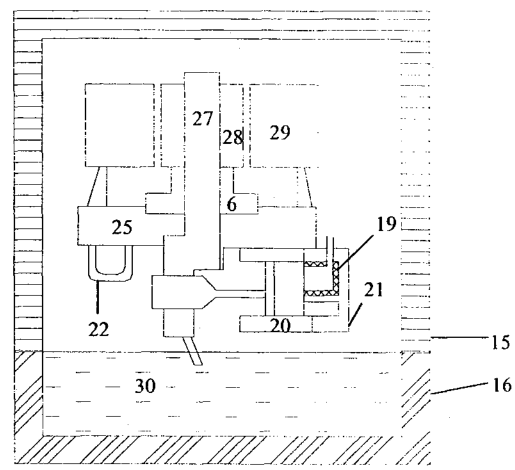

Fig. 2 Block diagram of lumped mass elements of body

Table 1 Names of lumped mass elements

Number	Names of lumped mass elements	Number	Names of lumped mass elements
1	Suction pipe gas	17	Suction muffler body
2	Gas in the shell	18	Pipe between suction muffler and suction plenum
3	Suction muffler inlet gas	19	Suction plenum body
4	Suction muffler gas	20	Cylinder body
5	Gas between suction muffler and suction plenum	21	Discharge plenum body
6	Suction plenum gas	22	Discharge muffler body
7	Suction chamber gas	23	Discharge pipe inside shell
8	Compression chamber gas	24	Discharge pine outside shell
9	Discharge plenum gas	25	Frame
10	Gas between discharge plenum and discharge muffler	26	Journal bearing
11	Discharge muffler gas	27	Crank shaft (with connecting rod)
12	Gas in the discharge line inside shell	28	Rotor
13	Gas in the discharge line outside shell	29	Stator
14	Suction pipe	30	Oil in Oil sump
15	Shell portion above oil sump	31	Return oil of the upper hole
16	Shell portion contacted with oil sump	32	Return oil of the lower hole

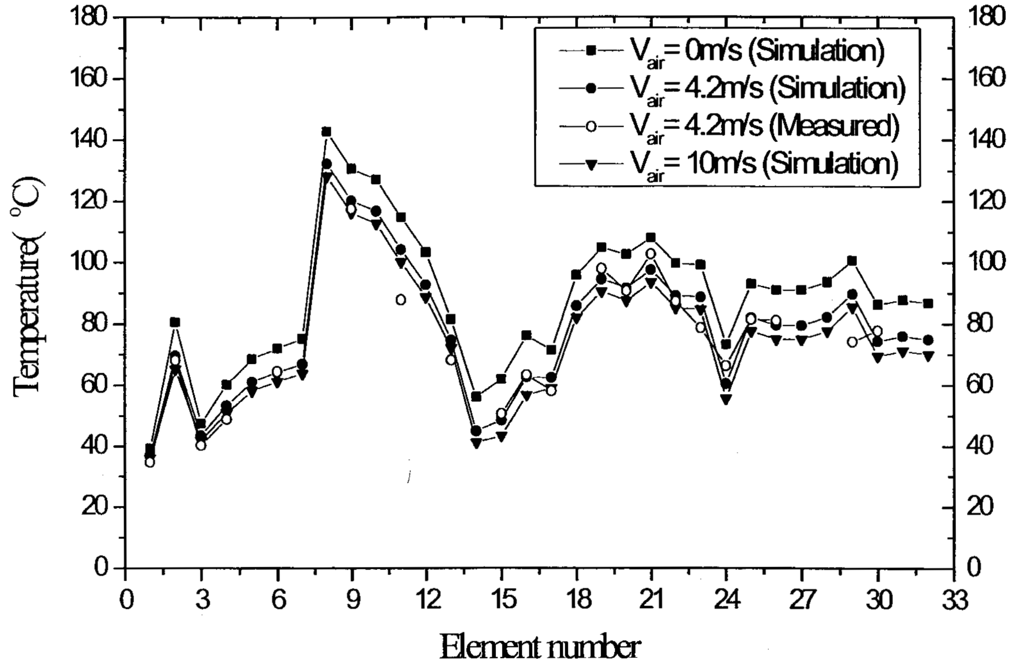

Fig. 3 Comparison of temperature of the elements between the measured value and the predicted value with air velocity (30℃ ambient temperature)

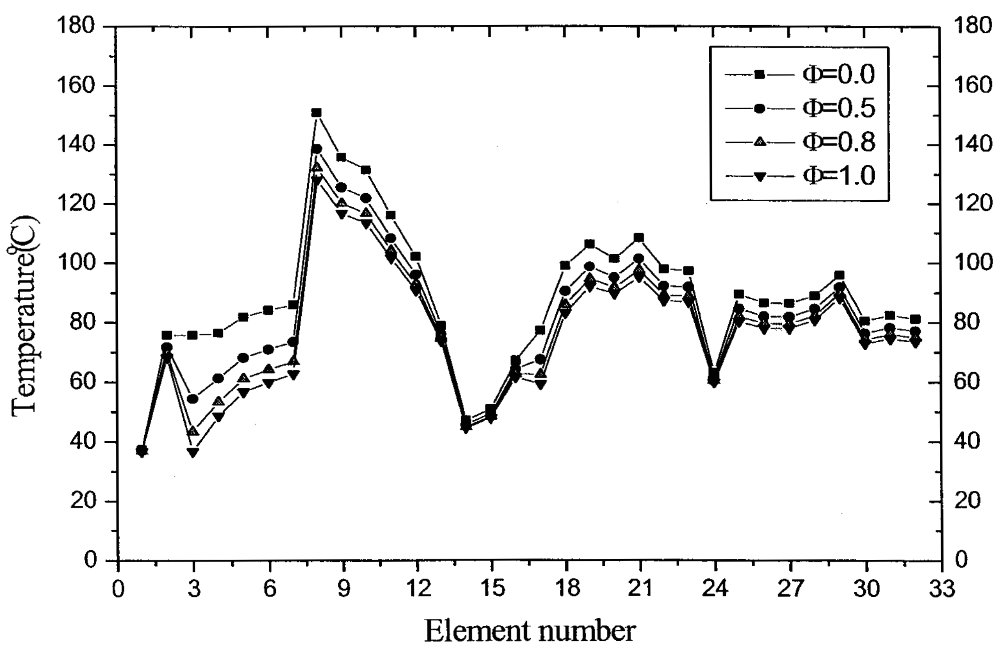

Fig. 4 Temperature distribution of the elements with mixing parameter (Φ)

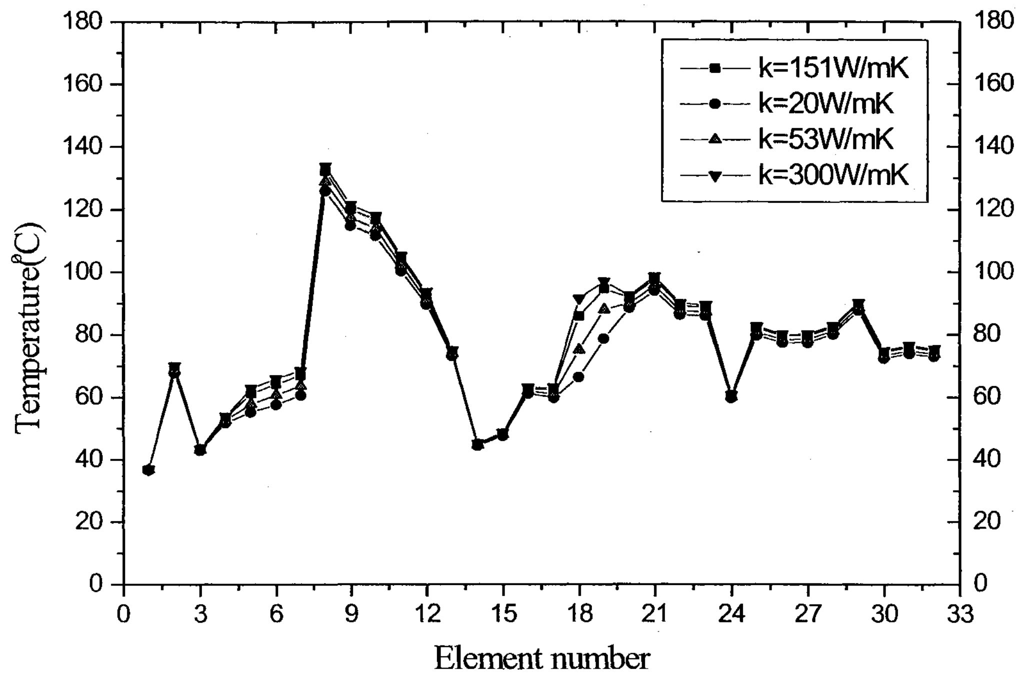

Fig. 5 Temperature distribution of the elements with thermal conductivity of the discharge plenum body

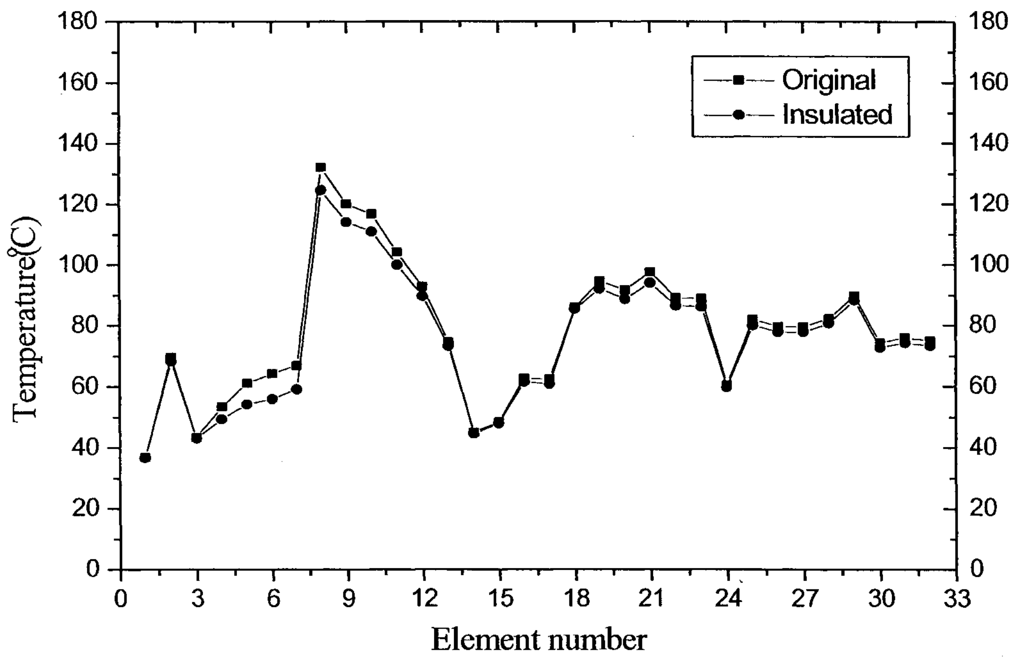

Fig. 6 Comparison of temperature of the elements between original and insulated case of suction system (1/2 overall heat transfer coefficient)

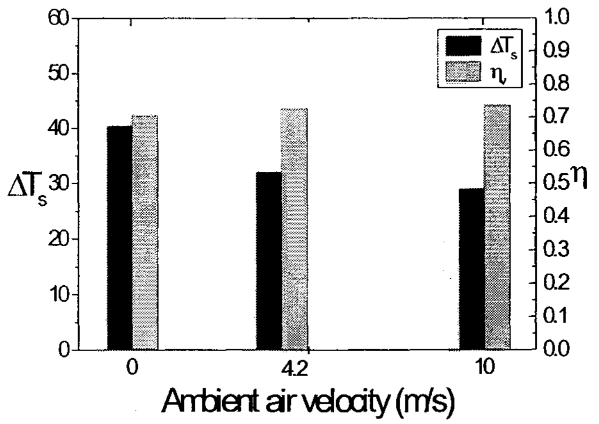

Fig. 7 Suction temperature increment and volumetric efficiency with ambient air velocity

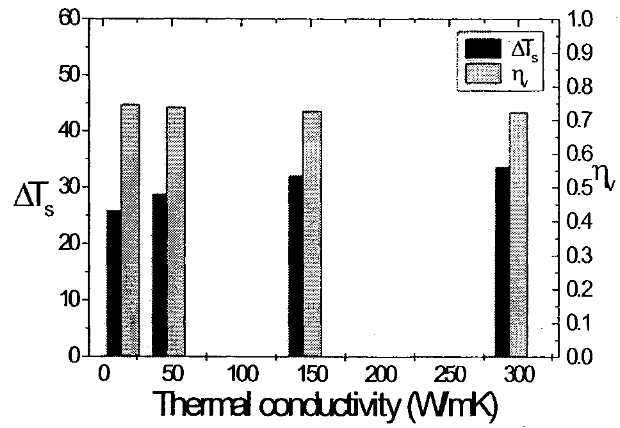

Fig. 9 Suction temperature increment and volumetric efficiency with thermal conductivities of discharge plenum body

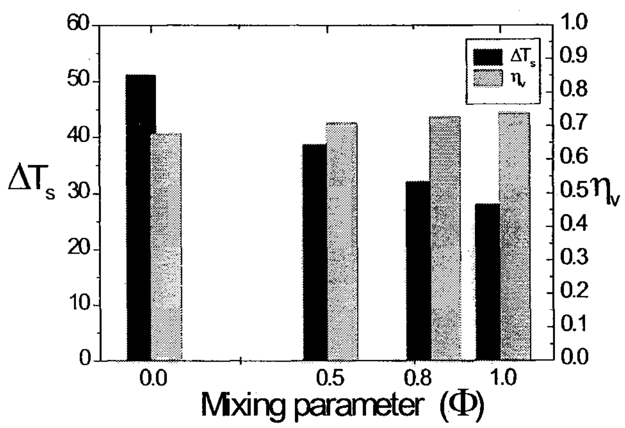

Fig. 8 Suction temperature increment and volumetric efficiency with mixing parameter

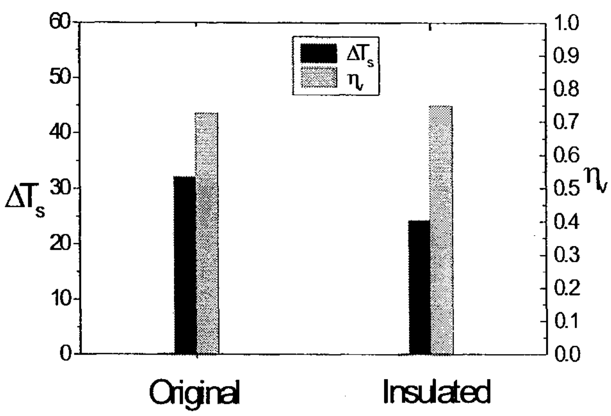

Fig. 10 Suction temperature increment and volumetric efficiency between original and insulated case of suction system